

Noncircular Outer Disks in Unbarred S0 Galaxies: NGC 502 and NGC 5485

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Strongly noncircular outer stellar disks have been found in two unbarred SA0 galaxies by means of analyzing spectroscopic data on the rotation of stars and photometric data on the shape and orientation of the isophotes. In NGC 502, the oval distortion of the disk is manifested as two elliptical rings, the inner and the outer ones, covering wide radial zones between the bulge and the disk and at the outer edge of the stellar disk. Such a structure may be a consequence of the so-called “dry” minor merger – multiple accretion of gas-free satellites. In NGC 5485, the kinematical major axis does not coincide with the orientation of isophotes in the disk-dominated region, and for this galaxy the conclusion about its global triaxial structure is unavoidable.

1 INTRODUCTION

The main part of galaxies in the nearby Universe are disk galaxies. It means that one of the large-scale components of their structure, often dominant, is just a stellar disk. From a dynamical point of view, stellar disks are “cold” systems, i.e., chaotic motions of stars there are small, and the bulk of their kinetic energy is confined to laminar circular rotation around the galactic center. Round lines of equal density (or of equal surface brightness) correspond to circular orbits, and, on the whole, the galactic disk, when viewed pole-on, looks like a regular circle. But how perfect is a circular shape of real galactic disks? This question worried researchers since the very rise of the extragalactic astronomy. The problem is complicated by the fact that we see any disk of a galaxy in projection onto the plane of the sky, at an arbitrary inclination, and it is not easy to distinguish the visible ellipticity produced by projection effects from the actual “intrinsic” disk ellipticity, especially in the case where we have to deal with individual objects and not with large samples. The average intrinsic ellipticity of stellar disks can be estimated statistically by studying their distribution over apparent isophote ellipticity under the assumption of a random orientation in space. In addition, since the assumption of circular gas rotation within the disks of galaxies is widely accepted while establishing the so-called scaling relations, for example, the TullyFisher relation, the scatter of galaxies observed around such relations also allows the intrinsic ellipticity of the disks to be constrained. Franx and de Zeeuw [9] had collected the photometric statistics and the statistics on the TullyFisher relation and had placed an upper limit onto the typical ellipticity of galactic disks, $\epsilon < 0.1$, by pointing out that it most likely lies within the range 0–0.06.

The paper by Rix and Zaritsky [20] can be mentioned as the first special work dedicated to this topic and based on highly accurate surface photometry of the disks of several individual galaxies. They had selected 18 galaxies seen nearly face-on judging that the rotation velocity projected onto the line of sight in the flat disks of such galaxies must be zero and, consequently,

the integrated 21-cm HI emission line must be very narrow. The K -band surface photometry was then performed to minimize the effect of dust and of the clumpy distribution of star-forming regions. The subsequent azimuthal Fourier analysis of the surface brightness distribution proved the disks to be actually rather circular, with a mean intrinsic ellipticity of 4.5%. The fact that such studies were impossible without invoking kinematic data when individual galaxies rather than average statistics were involved was obvious from the beginning, and new opportunities to solve the problem of the intrinsic ellipticity of galactic disks appeared with the development of integral-field spectroscopy. Andersen et al. [4] calculated the intrinsic disk ellipticity for seven Sb–Sc galaxies oriented nearly face-on by using both highly accurate red-band surface photometry and two-dimensional line-of-sight velocity fields obtained with the DensePak integral-field fiber spectrograph of the WIYN telescope. The true inclinations of the flat disks to the line of sight were determined from the two-dimensional ionized-gas kinematics. Their paper has a reference to the theoretical conclusion by Franx and de Zeeuw [9] that the method of tilted circular (*sic!*) rings can be applied to gas on elliptical orbits if the orbit ellipticity is small and if the rotation curve (the dependence of the rotation velocity on galactocentric distance) is flat. The conclusion about intrinsic ellipticity of the stellar disks was then derived from the shape of the outer isophotes. Its mean value turned out to be about 5%, in full agreement with the expectations, though the intrinsic disk ellipticity in two particular galaxies with close satellites which are possibly impacted by gravitational tides reached 20%.

In this paper, we consider two lenticular galaxies for which our data on the kinematics of the stellar components have turned out to be incompatible with the assumption about circular shape and circular rotation of the disks. In the second section, we describe the galaxies under consideration and the observational data used here. The evidence for the ellipticity of their stellar disks is formulated in the third section.

2 NGC 502 AND NGC 5485: NONINTERACTING S0 GALAXIES IN GROUPS

Table 1 provides the basic parameters of the galaxies under consideration which are accumulated in catalogs. Both targets are intermediate-luminosity lenticular galaxies; they are members of galaxy groups. However, while NGC 5485 is probably the central galaxy in its group [13, 10], NGC 502 is located on the periphery of its group, approximately at 300 kpc from the group central galaxy NGC 524, and only very faint satellites can be seen around it, within the radius of 100–150 kpc [14].

The galaxies to be discussed entered into a large sample of lenticular galaxies that we investigated by means of integral-field spectroscopy at the 6-m telescope of the Special Astrophysical Observatory belonging to the Russian Academy of Sciences (SAO RAS) [24]. In particular, two-dimensional velocity maps of the stellar components were constructed for the central regions. A misalignment of the kinematical and photometric major axes was detected even when the stellar kinematics of the innermost regions of NGC 502 and NGC 5485 was considered. In principle, this is not quite uncommon for the central regions of galaxies, but it is usually accompanied (and explained) by the presence of a bar at the galactic center violating axial symmetry in the gravity potential distribution and, accordingly, producing the consequent departure from a circular character of rotation. However, NGC 502 and NGC 5485 do not have not only bars but even hints of an oval bulge distortion; both galaxies are classified as SA0. We became interested in the unusual kinematics of the stellar components in these galaxies and undertook long-slit spectroscopy to see what happens in the outermost, disk-dominated regions of the galaxies. The slit was aligned with the major axes of the outer isophotes that must have coincided with the line of nodes of the disk plane under the assumption of the circular disk shape. To our great surprise, our spectroscopy with a long slit oriented in the presumed direction of the maximum rotation velocity projected onto the line of sight showed no rotation

Table 1: Global parameters of the galaxies

NGC	502	5485
Morphological type (NED ¹)	SA(r)0 ⁰	SA0 pec
Distance, Mpc (NED)	34	27
R_{25} (RC3 ²)	34''	70''
R_{25} , kpc	6.0	9.5
B_T^0 (RC3)	13.57	12.31
M_B (LEDA ³)	−19.3	−20.2
$(B - V)_T^0$ (RC3)	0.91	0.88
$(U - B)_T^0$ (RC3)	0.47	0.51
V_r (NED), km s ^{−1}	2524	1927
Inclination (LEDA)	24°	55°
PA_{phot} (R_{25})	60° ⁴	170° ²
σ_* , km s ^{−1} (LEDA)	103	195

¹NASA/IPAC Extragalactic Database.

²Third Reference Catalogue of Bright Galaxies [27].

³LyonMeudon Extragalactic Database.

⁴Il'ina and Sil'chenko [14].

in NGC 5485 and a very weak one in NGC 502! We decided to collect all necessary information to figure out what causes this phenomenon.

Our long-slit spectroscopy was performed at the 6-m SAO RAS telescope with the SCORPIO multimode focal reducer [1]. We obtained four cross-sections in total at different position angles for NGC 502 and several cross-sections at three different position angles for NGC 5485. A full log of observations listing the exposures used in our analysis is presented in Table 2. The observations were made mostly with a VPHG2300G grism and a slit width of 1 arcsec, that provided a spectral resolution of 2.2 Å being sufficient to measure stellar velocity dispersion in the disks. Only the last observation of NGC 5485 in 2015 was made with the new SCORPIO-2 version of the instrument [2], with a VPGH1200@540 grism and a spectral resolution of 5 Å. We measured the Doppler shifts of absorption lines by cross-correlating the pixel-by-pixel spectra taken along the slit at various distances from the galactic center with the spectra of bright

Table 2: Long-slit spectroscopy of the galaxies

Galaxy	Date	T(exp), min	PA_{slit}	FWHM, arcsec
NGC 502	Sep. 3, 2008	80	64	2.5
NGC 502	Sep. 3, 2008	80	334	1.6
NGC 502	Nov. 3, 2010	60	30	1.2
NGC 502	Nov. 3, 2010	120	15	1.2
NGC 5485	May 12, 2010	60	14	2.2
NGC 5485	Feb. 9, 2011	120	75	2.3
NGC 5485	Mar. 19, 2015	90	120	2.0

G8–K3 III stars and with the twilight spectra (G2 class) taken on the same nights with the same instrumentation setup. The data turned out to be deep enough to allow measuring the stellar kinematics up to the optical boundaries of the disks. The results of our measurements, namely, the radial profiles of the stellar line-of-sight velocities and velocity dispersions, are presented in Fig. 1 and Fig. 2. The radii where the velocity dispersions reached a low-level plateau were considered as cross-roads at which and beyond the spectra began to be dominated by the disk light. The radial ranges of the disk domination derived from the kinematical profiles of NGC 502 and NGC 5485 in this case have appeared to be consistent with exponential-shape intervals in the photometric surface brightness profiles (for the photometric data, see below).

Apart from the extended kinematical cross-sections obtained with a long slit, we had some two-dimensional line-of-sight velocity maps for the galactic centers obtained with integral-field spectrographs at our disposal. Both galaxies were observed within the ATLAS-3D project [7] with the SAURON spectrograph [5] at the 4.2-m William Herschel Telescope at La Palma; the raw data were downloaded from the public ING (Isaac Newton Group) archive of the Cambridge Institute of Astronomy and were reduced by our original technique [23]. The field of view of the SAURON spectrograph is $33'' \times 41''$, a single spatial element is $0.94''$, and the spectral resolution is about 4 \AA . In addition, NGC 5485 was also observed as a part of the CALIFA project [21, 11] with the PMAS/PPAK integral-field spectrograph at the 3.5-m telescope of the Calar Alto Observatory, and we used the already reduced public data cube with a spectral

resolution of 500 and a spatial element of $1''$ (the spatial resolution is about $3''$) to construct the velocity fields for the stellar component and the ionized gas present at the center of this lenticular galaxy, for a $60'' \times 40''$ area. The velocity fields for NGC 502 and NGC 5485 are shown in Fig. 3 and Fig. 4. They were analyzed by the tilted-ring method under Moiseevs modification – by the DETKA code [19]. The orientation of the kinematical major axis, which in the case of a circular rotation must be coincident with the line of nodes of the disk plane, was traced up to a distance from the center of about $20''$ in NGC 502 and up to $25''$ in NGC 5485. Although these distances are defined by the quality of the stellar velocity fields, by chance, they are at the beginning of the galactic exponential disks.

The photometric analysis of the structure of these galaxies is abundantly presented in the literature. In particular, deep photometry of NGC 502 performed with the SCORPIO focal reducer of the 6-m SAO RAS telescope in the direct-image mode was described in detail by Ilina and Silchenko [14]; the presence of wide stellar rings (surface brightness excesses) between $8'' - 16''$ and $35'' - 45''$ was pointed out. A two-dimensional decomposition of the NGC 5485 image was undertaken by Méndez-Abreu et al. [18], Laurikainen et al. [16, 17], and Gutiérrez et al. [12], where significantly differing metric parameters of the galactic disk and bulge are presented. We additionally undertaken an isophotal analysis of the r -band images of both galaxies based on SDSS data, release 9 [3], and of the $4.5\text{-}\mu\text{m}$ image of NGC 5485 retrieved from the public database of the S4G survey [22], though the latter image is at the edge of the field of view of the Spitzer telescope and, therefore, the characteristics of the outer isophotes are not very sure. Figure 5 compares the kinematical and photometric parameters: the ellipticities measured within our isophotal analysis are compared with $1 - \cos i$, where the inclinations of the disk plane to the plane of the sky, i , were obtained by the tilted-ring method applied to the two-dimensional velocity fields; the orientations of the kinematical and photometric major axes in the central regions of the galaxies are also compared. As it was expected, the kinematical and photometric major axes in the central regions of the galaxies have appeared to be strongly

misaligned. The parameters of the isophotes farther from the center, into the region where the exponential stellar disks dominate in the surface brightness, are also traced in Fig. 5.

3 THE ELLIPTICAL OUTER DISKS IN NGC 502 AND NGC 5485

Let us consider in detail orientations of the NGC 502' and NGC 5485' disks in space by using all the available photometric and kinematical information.

NGC 502. According to the results of our isophotal analysis, after inspecting the surface brightness profile ([14]; also see Fig. 6, left), we conclude that the inner ring in NGC 502 is localized near the radius of $15''$; it is also clearly seen by eye in the combined-coloured SDSS image. Since we have also the results of integral-field spectroscopy, namely, the two-dimensional stellar velocity field just for this radial zone, we find that the kinematical and photometric major axes in this region are misaligned by some 30° . Obviously, the inner ring of NGC 502 has elliptical shape. Starting from the radius of $20''$, the surface brightness profile reveals exponential shape, and the stellar velocity dispersion profile (Fig. 1) flattens out at $\sigma_* \sim 60 \text{ km s}^{-1}$. Obviously, here we deal with the area of stellar disk domination in the surface brightness and in the matter density. What is the orientation of this disk in space? According to the integral-field spectroscopy, the kinematical major axis reaches $PA \approx 203^\circ$ at the radius of $R = 16'' - 18''$; the isophotes in the radius range of $R = 22'' - 30''$, beyond the influence of the inner ring, in the region of exponential disk domination, show approximately the same position angle of the major axis: $PA_{phot} = 204^\circ$ according to our B-band data from SCORPIO [14] and $PA_{phot} = 201^\circ$ according to the r -band SDSS data. We would conclude that we see a round stellar disk oriented nearly face-on in the radius range of $R = 22'' - 30''$: the apparent ellipticity of the isophotes in this radius range is $1 - b/a = 0.08$, that corresponds to the inclination of 23° for the case of a very thin disk and is consistent with the photometric inclination of 24° from the HYPERLEDA database (see Table 1). Interestingly, the kinematical

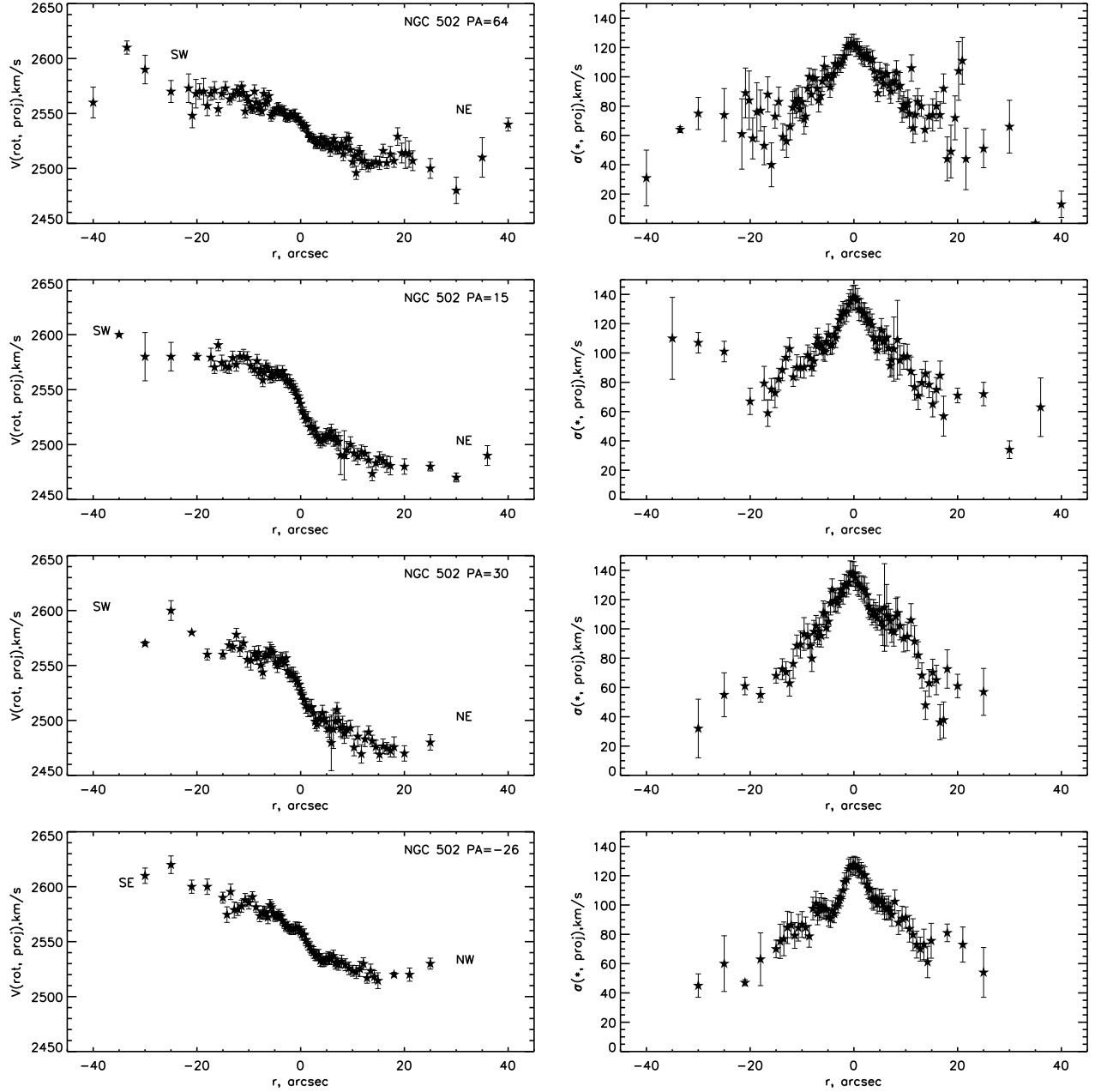


Figure 1: Kinematical cross-sections obtained for NGC 502 with the SCORPIO spectrograph in the long-slit mode at the 6-m SAO RAS telescope at four different position angles: the stellar line-of-sight velocities (*left*) and the corresponding stellar velocity dispersions (*right*).

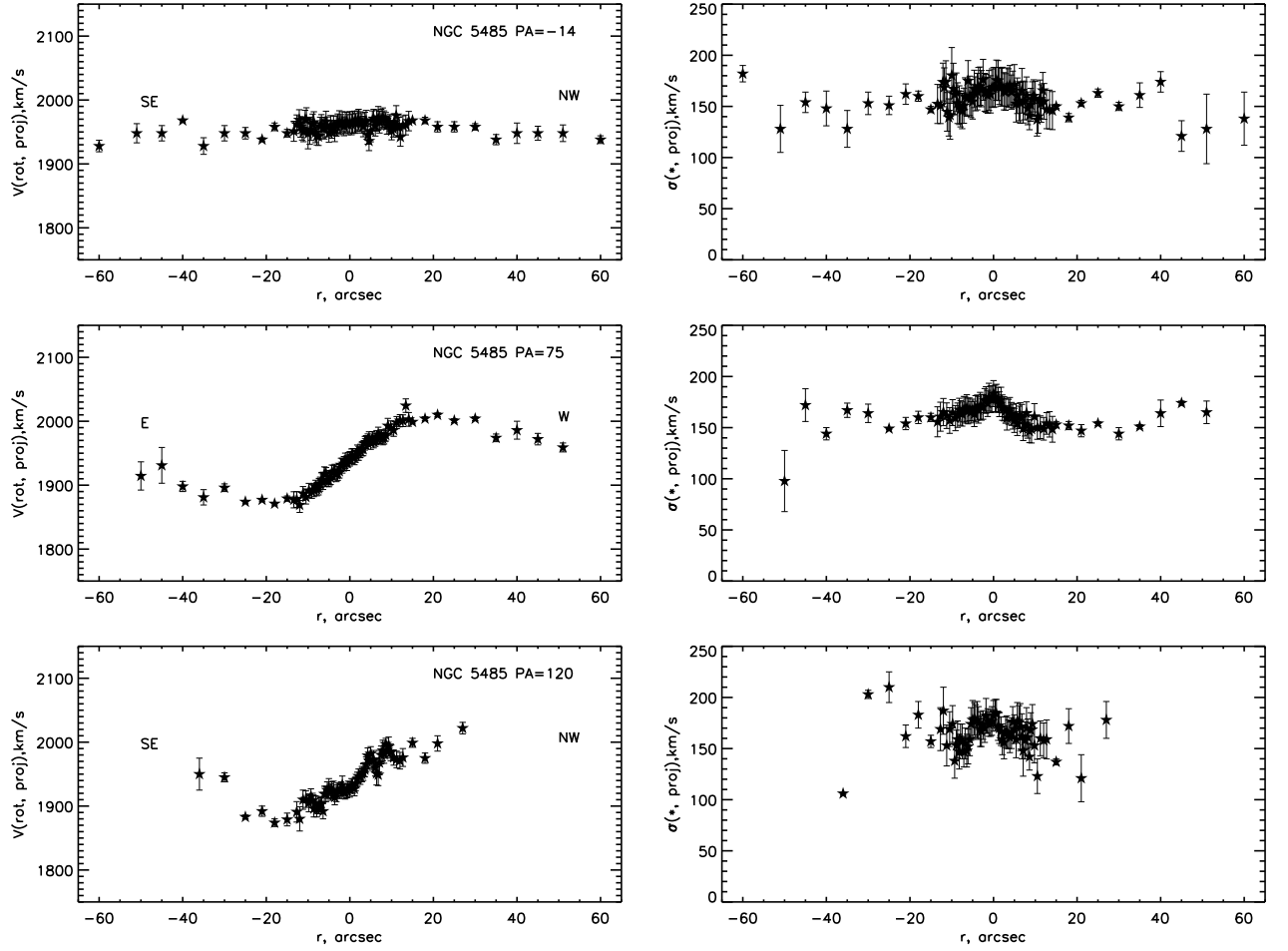


Figure 2: Kinematical cross-sections obtained for NGC 5485 with the SCORPIO spectrograph in the long-slit mode at the 6-m SAO RAS telescope at three different position angles: the stellar line-of-sight velocities (*left*) and the corresponding stellar velocity dispersions (*right*).

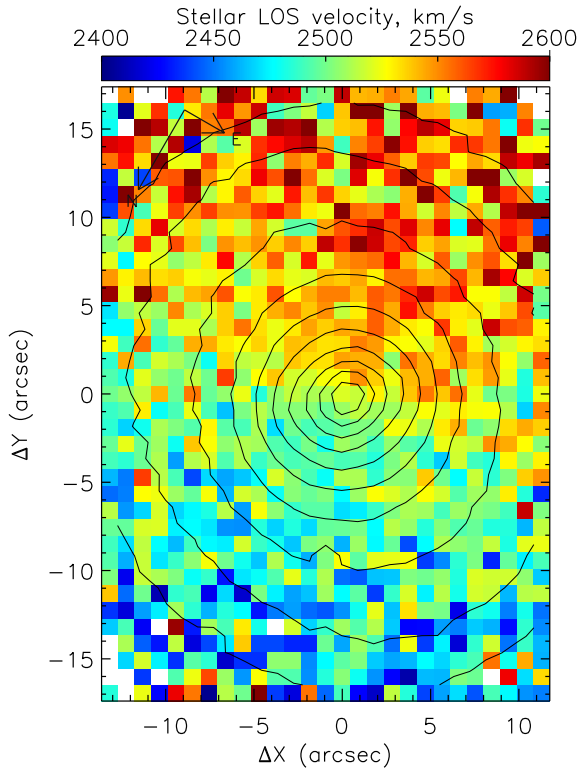


Figure 3: Stellar velocity field for NGC 502 calculated using data from the SAURON integral-field spectrograph. The orientation of the picture is indicated by the arrows directed to the north and the east in the upper left corner of the map. The surface brightness distribution in continuum at a wavelength of 5100 \AA is superimposed by the isophotes.

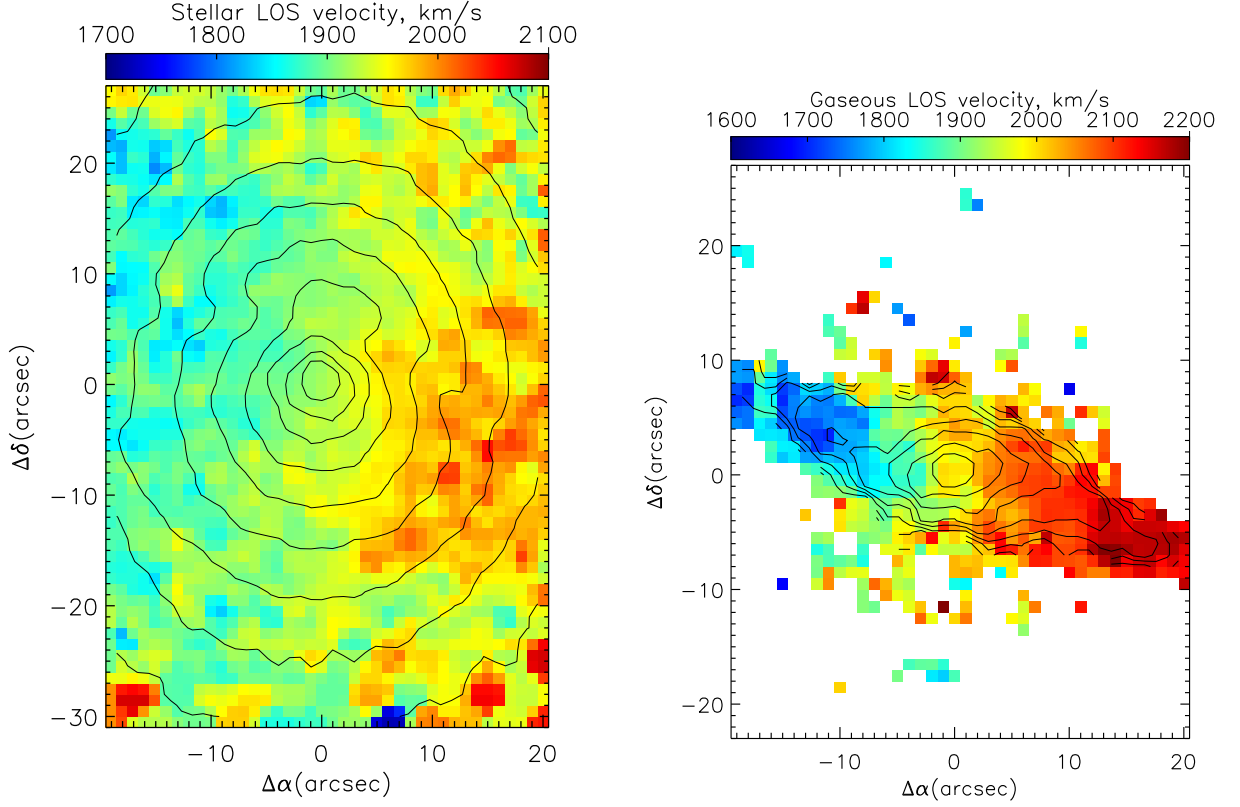


Figure 4: Stellar and ionized-gas (by measuring the $[\text{NII}]\lambda 6583$ emission line, the strongest one in the optical range in this galaxy) velocity fields for NGC 5485 calculated using the data from the PMAS integral-field spectrograph obtained as part of the the CALIFA project. The surface brightness distribution in continuum at a wavelength of 5100 \AA (*left*) for the stellar velocity field) and the $[\text{N II}]\lambda 6583$ emission line flux distribution (*right*) for the ionized-gas velocity field) are superimposed by isophotes.

inclination at $R > 16''$ is also consistent with the photometric one under the assumption of a thin disk (Fig. 5, left). We shall take these orientation angles, $i = 23^\circ$ and the position angle of the line of nodes $PA_0 = 202.5^\circ$, as characterizing the orientation of the NGC 502' disk in space, and shall attempt to bring all the four kinematic cross-sections of Fig. 1 into one rotation curve under the assumption of circular bulk motions. The result of our calculation is shown in Fig. 7, left. Inside the radius of disk-domination starting, at $R < 20''$, the rotation curve is shown which is constructed from the SAURON two-dimensional velocity field by the method of tilted, intrinsically circular rings fixing the inclination of the rotation plane and allowing the position angle of the line of nodes to change freely along the radius; whereas at $R > 20''$ different symbols indicate our four cross-sections of Fig. 1 with a long-slit velocity measurements recalculated to the circular rotation velocities under the fixed orientation angles of the rotation plane specified above. The result has turned out to be good: within the error limits, in the range $R = 22'' - 30''$, all four cross-sections have shown similar maximum stellar rotation velocities, about 145 km s^{-1} , which, besides all, also corresponds to the luminosity of NGC 502 if we refer to the TullyFisher relation, for example, from Theureau et al. [26]. However, beyond the standard optical radius of the stellar disk, at $R > 35''$, the calculated rotation velocity drops sharply (Fig. 7, left), the position angle of the isophotes increases sharply (Fig. 5, left bottom), and another ring is observed in the surface brightness profile [14]. Obviously, the outer wide ring of NGC 502 is also elliptical. Figure 8 shows the isophotal ellipticity for the image of NGC 502 deprojected toward the view face-on by using the orientation parameters specified above. We see two distinct ellipticity peaks in the inner region, at $R = 3.5''$ and $R = 15''$, corresponding to the nuclear bar and to the inner ring, while in the outer parts of the disk, at $R > 30''$, the intrinsic disk ellipticity begins to rise monotonically, and reaches 10% at $R = 42''$. The galaxy's deep image obtained with the MegaCam camera at the CanadaFranceHawaii Telescope (CFHT) shows numerous stellar shells in the outer regions [8]. Obviously, despite the relative isolation of NGC 502, it suffered a number of minor mergers, probably with dwarf galaxies devoid of gas,

which could produce an oval distortion of some zones at fixed radii of the (globally) dynamically cold stellar disk.

NGC 5485. As it can be seen in Fig. 5, right bottom, the kinematical major axis in the central part of NGC 5485 is exactly perpendicular to the photometric major axis. This allowed Krajnovic et al. [15] to put NGC 5485 in the rare subclass of galaxies (consisting of only two objects in the nearby, $D < 42$ Mpc, Universe) with the so-called prolate rotation, when the stellar rotation axis coincides with the longest axis of the spheroid in a triaxial potential. Even significantly earlier than the ATLAS-3D survey, Wagner et al. [28] stated prolate rotation in NGC 5485 by analyzing long-slit spectroscopy data up to a distance of $22''$ from the center. Actually, no one of them determined an exact orientation of the stellar rotation axis in this galaxy. These authors only compared the position angles of the kinematical and photometric major axes, mainly for the central region of the galaxy, where the bulge dominates in the surface brightness. The idea of general triaxiality of NGC 5485, when the entire galaxy is an ellipsoid with three different axes, without a flat disk, comes into conflict with the constancy (along the radius) of the position angle of the photometric major axis (isophotes) over the entire galaxy and with the constancy of the apparent isophotal ellipticity within the area dominated by the exponential galactic disk at $R > 30''$. All the photometrists [17, 12] classified this galaxy as unbarred lenticular one, i.e., as an axisymmetric body. Since there is a dust lane near the galactic center and since the gaseous disk coincident with it rotates with the same orientation of the kinematical major axis as the stars (Fig. 4), it is tempting to suggest that we see rotation of the stellar component formed from accreted gas with a polar angular momentum at the galactic center up to a distance of $22''$ from the nucleus. However, whereas the gas is concentrated in a disk seen nearly edge-on, with an inclination of about $70^\circ 80^{circ}$ in its outer parts, the rotation of the stellar component analyzed with the tilted-ring method provides evidence for a much more moderate inclination of the rotation plane (45° according to the SAURON data and $\leq 37^\circ$ according to the CALIFA data); and, obviously, there are no

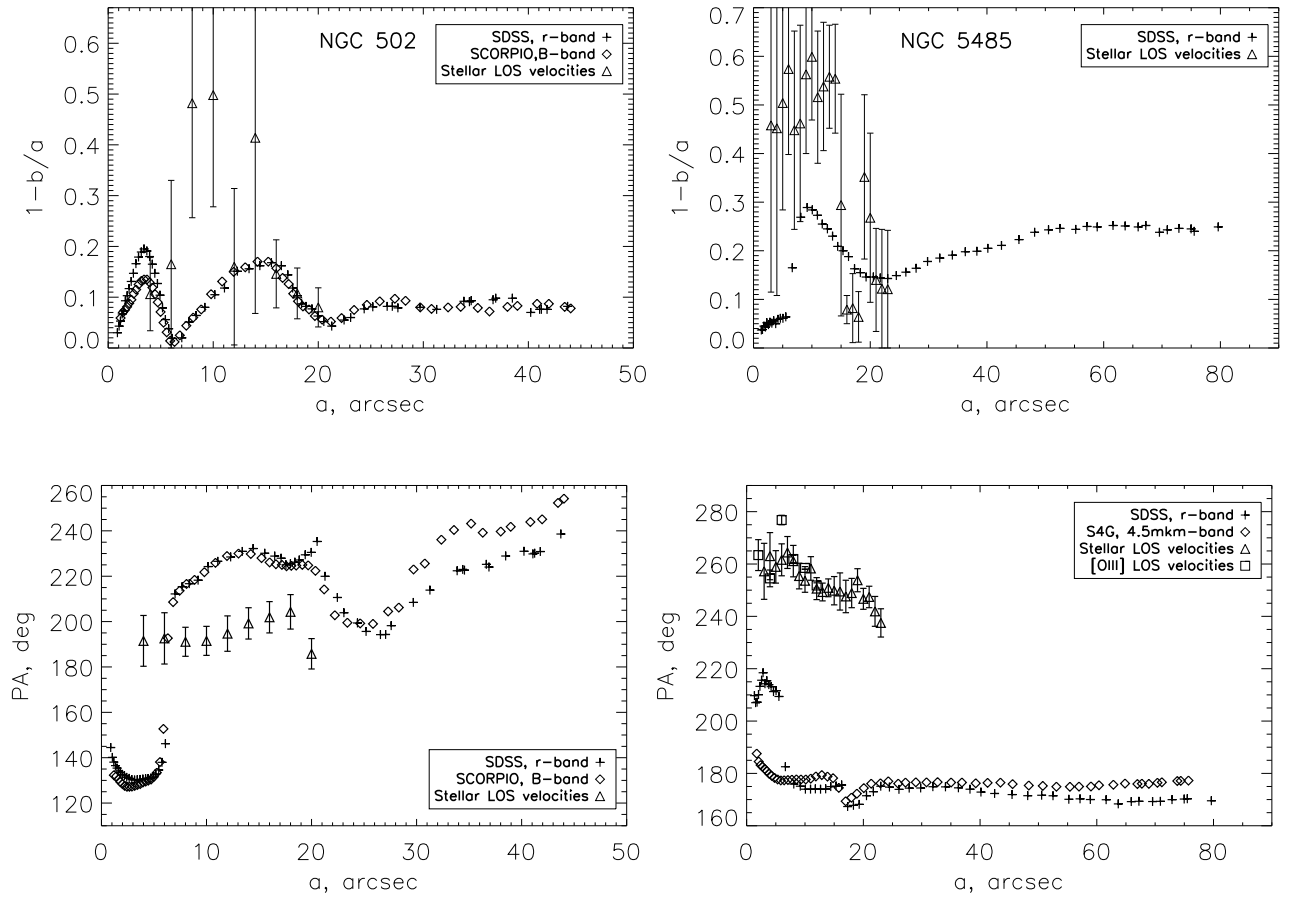


Figure 5: Isophotal ellipticities and orientations of the photometric and kinematical major axes in NGC 502 (*left*) and NGC 5485 (*right*).

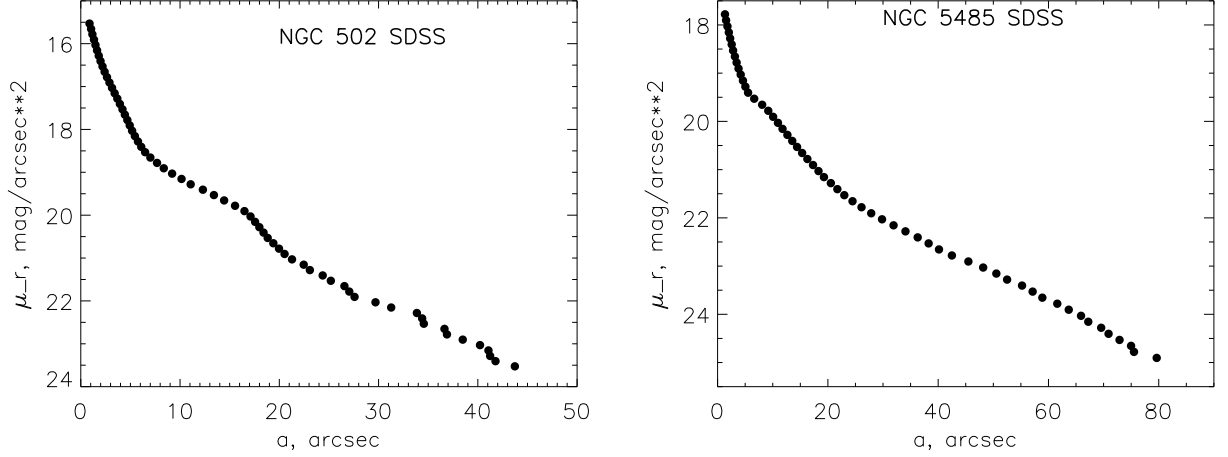


Figure 6: Azimuthally averaged (with isophotal parameters sliding along the radius) surface brightness profiles for NGC 502 (*left*) and NGC 5485 (*right*), from the SDSS data.

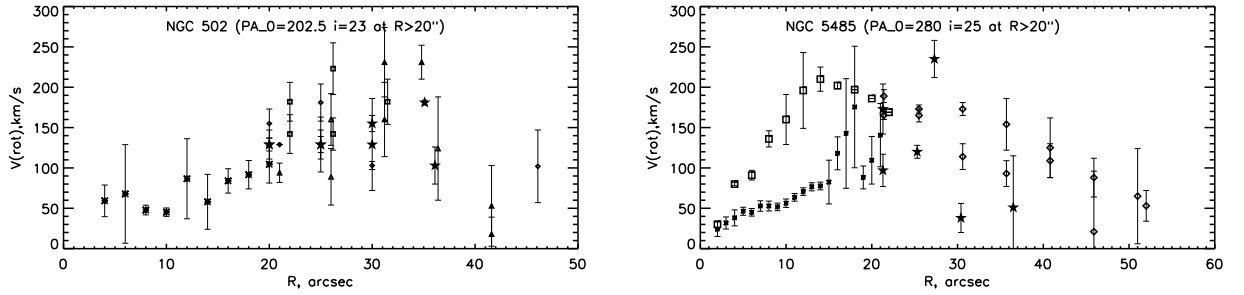


Figure 7: Radial circular velocity profiles under the assumption of a circular rotation of the stellar disks in NGC 502 (*left*) and NGC 5485 (*right*) (uncorrected for the asymmetric drift). The inner regions, $R < 20''$, are the stellar rotation curves (asteriks) constructed by the tilted-ring method from the two-dimensional line-of-sight velocity maps. In the outer regions, various other symbols indicate the stellar line-of-sight velocity profiles at various position angles recalculated into the circular rotation velocities with the orientation parameters of the rotation planes specified at the top of the plots. For NGC 5485, the squares also indicate the gas rotation curve obtained through a one-dimensional cut along the kinematical major axis of the line-of-sight velocity field for a gaseous disk seen nearly edge-on.

signatures of a strongly inclined “nested” stellar disk in the isophotes. Even greater difficulties arise with the interpretation of the stellar rotation beyond the central part of the galaxy and beyond the polar gas concentration. If we attempt to bring the three cross-sections in Fig. 2 into one circular rotation curve under the assumption of an axisymmetric disk using the photometric orientation angles, $PA_0 = 170^\circ$ and the inclination of 45° , then recalculating the cross-section taken at $PA = 75^\circ$ would give a rotation velocity greater than 1500 km s^{-1} , while recalculating the cross-section taken at $PA = -14^\circ$ would give rotation velocities close to zero. Obviously, this approach does not work. Formally, we can attempt to select the orientation of the plane of quasi-circular stellar rotation basing on the similarity of the spectral cross-sections at $PA = 75^\circ$ and 120° (Fig. 2); the kinematical major axis must be somewhere between these directions. Figure 7, right, presents the result of successful convergence of the three kinematical cross-sections into one rotation curve made for the following orientation of the plane of quasi-circular rotation: $PA_0 = 100^\circ$ and $i = 25^\circ$. Under such inclination of the rotation plane, the maximum disk rotation velocity turns out to be about 180 km s^{-1} , which agrees excellently with the TullyFisher relation in the near infrared by Theureau et al. [26]. The inner part of the circular rotation curve calculated from the gaseous velocity field by applying one-dimensional digital cut along the major axis to the ionized-gas line-of-sight velocity field presented in Fig. 4, right, also joins excellently to (or is continued by) this rotation curve of the stellar component. However, such orientation angles have no analog whatsoever in the photometric characteristics of the galaxy. And at radii greater than $40''$, the rotation curve in Fig. 7, right, falls to zero, that completely disagrees with the expected shape of the rotation curve for an exponential disk with a scalelength of 4.5 kpc, or about $33''$ [16] that must reach its maximum at a radius approximately equal to two exponential scalelengths. The hypothesis of axial symmetry, even of the partial one, in the case of NGC 5485 should apparently be abandoned.

4 CONCLUSIONS

We have investigated in detail two unbarred lenticular galaxies for which our previous spectroscopic data have shown a misalignment of the kinematical and photometric major axes. The anomaly of the large-scale stellar kinematics in NGC 502 has turned out to be related to the presence of two wide elliptical stellar rings that border an otherwise normal stellar disk from the inside (adjacent to the bulge) and from the outside (near the optical boundaries of the galaxy).

As for NGC 5485, the situation is obviously more complicated: we have failed to identify an axisymmetric structural component in the galaxy at any distance from the center. The rotation axis of the galactic bulge coincides in projection with the major axis of the isophotes; this component may be genetically related to the accreted polar gas observed at the center of NGC 5485 as a disk consisting of gas and dust seen nearly edge-on. However, the central stellar component of NGC 5485 is definitely not a thin disk but most likely a bulge, i.e., the so-called prolate spheroid. It should be noted that the stellar population of the bulge is old, $T_{SSP} \sim 9$ Gyr [25]. It means that even if this component is formed from the accreted gas, this event has occurred very long ago, and the ionized gas is in stable rotation on a polar orbit without forming any stars for the last many billions of years. The anomaly pointed out by Baes et al. [6] is also consistent with this fact: despite a noticeable amount of dust, neither neutral nor molecular hydrogen has been detected in the galaxy to a very deep limit. The large-scale stellar disk of NGC 5485 is definitely noncircular, because the kinematical major axis at a radius greater than $25''$ is projected at a position angle $PA_0 = 100^\circ$, that does not coincide with the position angle of the major axis of the isophotes. If the outer component is a disk, as suggested by the exponential surface brightness profile, then it has an intrinsically elliptical shape and exhibits a highly noncircular stellar rotation.

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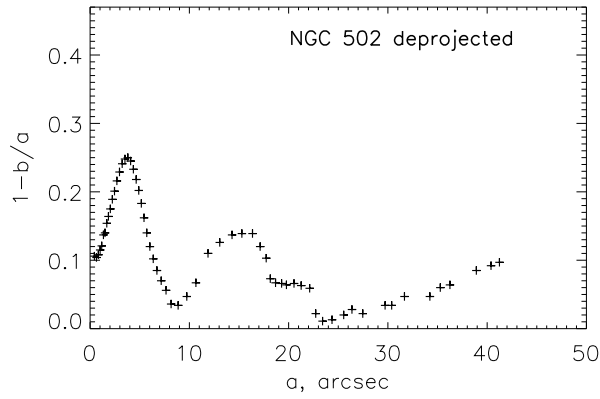


Figure 8: Intrinsic ellipticities of the isophotes in the image of NGC 502 (SDSS, the r -band) deprojected by assuming the following orientation of the galactic plane in space: the disk inclination to the plane of the sky is $i = 23^\circ$, the position angle of the disk line of nodes is $PA_0 = 202.5^\circ$.

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